DYNAMIC SIMULATIONS OF CANCELLOUS BONE RESORPTION AROUND ORTHOPAEDIC FIXATIVE IMPLANTS

A. Gefen

Department of Biomedical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, ISRAEL

Abstract- **Progressive loosening of bone fixation screws is a well-documented phenomenon, induced by stress shielding and subsequent adaptive bone remodeling which results in bone loss around the screw. A set of two-dimensional computational (finite element) models was developed in order to test the effect of various screw profiles on the predicted extent of bone resorption. An algorithm simulating local bone adaptation to mechanical stimuli was developed and subsequently used to evaluate the biomechanical performances of the different screw profiles analyzed, i.e., triangular, rectangular and trapezoidal thread shapes. This remodeling algorithm predicted local bone gain or loss in the vicinity of the screw as a response to the resulted mechanical stress distribution. A dimensionless set of stress intensity parameters (SIP) was developed to quantify the bone-screw stress transfer, enabling a convenient rating of different screw performances according to the nature of expected adaptation of the surrounding bone. The results indicated that a wide rectangular screw profile is of superior biomechanical compatibility with bone compared to the other profile types. The present work demonstrated that bone remodeling computer simulations can be used as a powerful tool for evaluation of different design parameters of fixative screws, such as geometry, material characteristics and even coatings.**
Keywords - Bone modeling/remodeling, adaptation, screw design

I. INTRODUCTION

Bone screws are well-known and clinically accepted alternatives for plate fixation of bone fractures or for stabilizing bone transplants. However, since these screws remain attached to the bony tissue after it was healed, they may also diminish its strength and stiffness: the significantly stiffer metallic screws (elastic modulus of 100 to 200 GPa) carry most of the shared load, causing the adjacent bone (elastic modulus of 1-20 GPa) to be atrophied in response to the diminished load it is carrying. This effect of metallic bone screws on the bony tissue in the vicinity of the screw is called "stress shielding". The aim of this study was to characterize screw designs that provide optimal stress transfer to the surrounding bone, and, thereby, alleviate commonly observed conditions of loosening and failure of plate fixations due to stress shielding [1], [2].

II. METHODOLOGY

Two finite element two-dimensional (2D) model types of the bone-screw interaction were developed. The first is an idealized axisymmetrical model of a bone cylinder with an outer cortical surface and an inner trabecular bulk (Fig. 1). A screw is inserted perpendicularly to the bone surface, loading the modeled bone with axial tensile force and screw-to-bone contact conditions. This not only permits easy creation of models, but also provides a tool for basic comparisons of screw performances, by isolating the effect of screw engineering design parameters. Other structural and physiological effects (e.g. those of the complex

musculoskeletal loading system) can thereby be excluded. The second 2D model type was selected to be that of the proximal femur, implanted with different bone screw types (Fig. 2). The latter modeling approach was selected because the musculoskeletal loading system of the hip joint has been extensively studied by others and may be regarded as a benchmark problem in the field of bone adaptation.
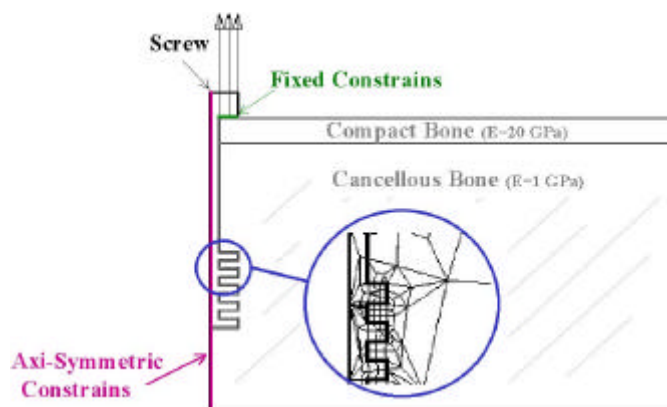

Fig. 1. The idealized axisymmetrical model of a bone cylinder with an outer cortical surface and an inner trabecular bulk. The finite element mesh around the screw threads is magnified.
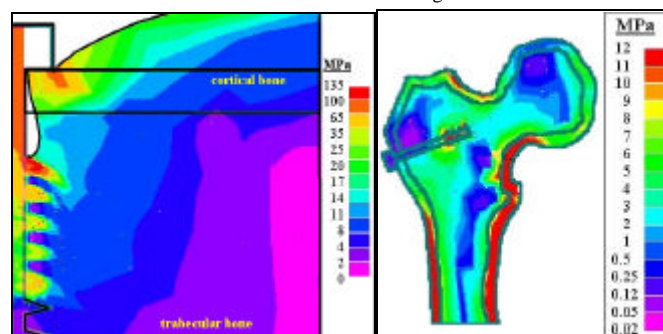

Fig. 2. The von Mises stress distribution within two-dimensional computational models of an idealized axisymmetric screw-bone interaction (left) and the femoral head following implantation of a fixative screw with a triangular thread profile (right).

While conventional FE models of the musculoskeletal system provide detailed information concerning the internal stress distribution, they reveal nothing of the long-term effects of changes in bone stresses. The coupling of the FE method with a quantitative bone remodeling theory allows the study of both the stress state and the internal bony morphology as changes occur in both. Fig. 3 depicts the approach by which Wolffs law was formulated to simulate bone adaptation. Compression tests of human trabecular bone showed that for a physiological strain rate (0.01 per sec), the elastic modulus of the bone specimen is proportional to the cube of the apparent bone density [3]. This relation, which was shown to hold for bony tissue in the entire skeleton, allows meaningful predictions of local bone density based on its stiffness distribution.

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Abstract

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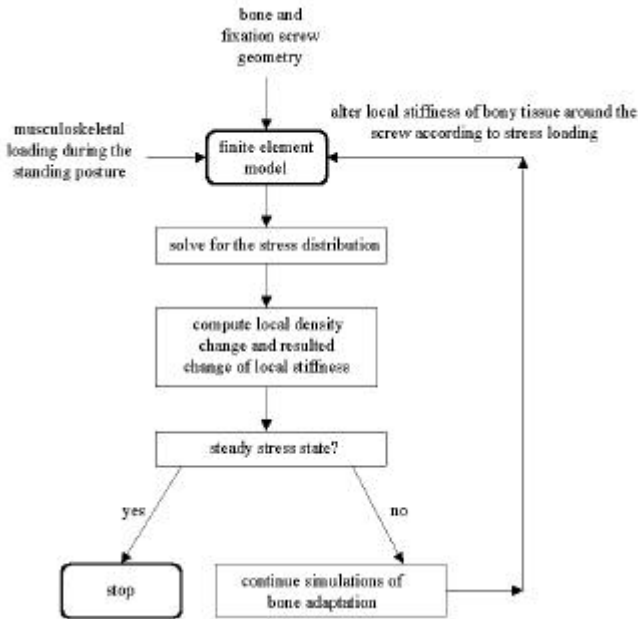| Classification of Abstract	Limitation of Abstract
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Fig. 3. Outline of the bone adaptation simulation procedure.

Starting from a 2D homogenous distribution of bone stiffness and density (1.85 and 0.9 gr/cm^3 for the cortical and trabecular components, respectively), an incremental, time-dependant technique was employed to simulate the bone density distribution around the screw implant for a characteristic static musculoskeletal loading. According to the resultant stress distribution, calculated by means of the ANSYS FE software package, local stiffness values of the bone surrounding the screw were altered (in intervals of 0.04 gr/cm^3), to simulate the progress of modeling/remodeling over a certain time interval (the local stimuli for bone adaptation was assumed to be determined only by the local mechanical stress). If the local density/stiffness were changed by more than a preset threshold value (%1 change from the previous iteration), bone stresses were reevaluated for the new stress distribution and the remodeling simulations were continued, until a steady state of stresses was reached.

In order to evaluate the quantity of loads that are transferred between the screw and the cancellous bone and their alteration with time due to bone adaptation, it is convenient to use ratios between averaged stresses in pre-defined regions of interest (ROI) within the cancellous bone and within the screw. These ratios are termed stress intensity parameters (SIP) [4]. Two SIP were defined as means for calculating the screw-bone stress transfer:

$$\alpha = \frac{\sigma_{fb}}{\sigma_{ft}} \quad (1)$$

$$\beta = \frac{\sum_{i=2}^{N} \sigma_{b_i}}{\sum_{i=2}^{N} \sigma_{t_i}} \quad (2)$$

The ROI for calculation of averaged stresses are marked on Fig. 4. The first SIP (1), a, equals the averaged stresses in the bone volume above the first thread of the screw (s_{fb}) divided by the averaged stresses within the metallic first thread (s_{ft}); the second SIP (2), b, is the average of ratios of the stresses in bone between adjacent threads (s_{bi}) and stresses within the corresponding metallic threads (s_{ti}), not including the first.
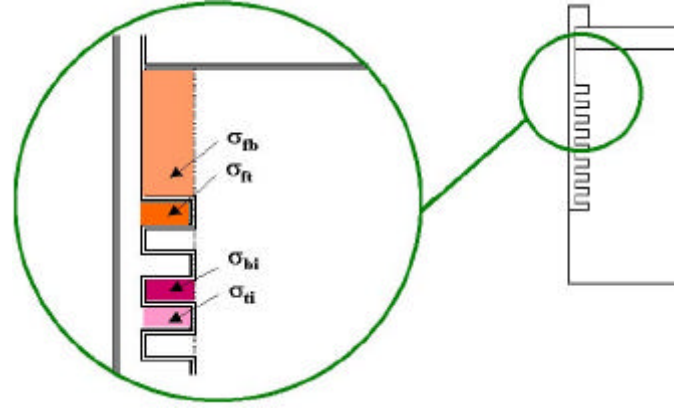

Fig. 4. Definition of the Stress Intensity Parameters (SIP) for evaluation of the screw-bone stress transfer

Since the bone is compressed between the first thread of the fixative screw and the head of the screw, the first thread carries a substantial load, which may cause stress concentrations to appear above it. For this reason, SIP evaluations of the screw-bone stress transfer were carried out separately for the first thread (1), and for all other threads (2). Utilization of these dimensionless SIP provided a convenient tool for evaluation of the stress transfer. Ideally, for a screw made of a material with properties identical to those of bone, a homogeneous stress transfer will result. In this case, stress shielding will be eliminated as the screw and the adjacent bone will share similar loads, and the values of the SIP will approach the ideal magnitude of 1. The adaptation process (Fig. 3) was activated for the different screw designs under evaluation, i.e., triangular, rectangular and trapezoidal thread shapes. Following each computational iteration (which simulated a time interval of 10.6 weeks), the SIP (1),(2) were calculated.

III. RESULTS

The computer simulations of the evolution of the SIP versus time is shown in Fig. 5 and Fig. 6 for the different bone screw designs under evaluation (using the idealized model of Fig. 1). As detailed in the Methodology section, greater values of the SIP are desired, as these indicate a more optimal sharing of loads between the fixative screw and the surrounding cancellous bone.
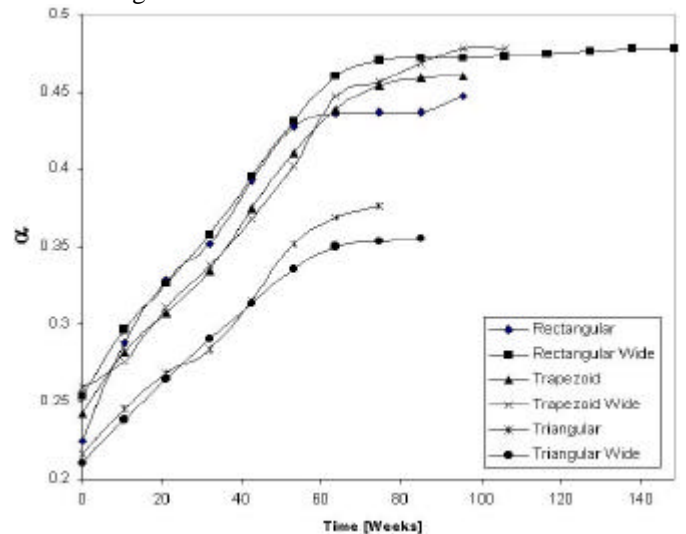

Fig. 5. Predicted stress transfer between the first thread of different bone screw designs and the surrounding cancellous bone versus time.
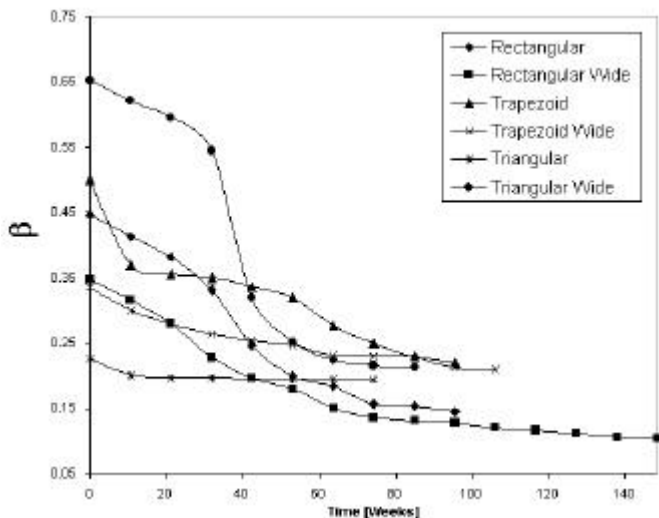
Fig. 6. Predicted averaged stress transfer between the threads (excluding the first thread) of different bone screw designs and the surrounding cancellous bone versus time.

According to the SIP criteria, the best initial state is provided by the wide threaded triangular screw (=0.652 immediately following implantation). The loosening process of the wide rectangular screw was predicted to be the longest one, as bone density in the vicinity of the screw did not drop beneath the critical value of 0.3 gr/cm^3 until as many as 148 weeks were simulated to elapse. Contrarily, the screw with the triangular profile demonstrated the poorest performances, providing the shortest duration for expected loosening and micromotion (74 weeks). Model predictions of the expected duration for initiation of implant loosening and micromotion in the femoral head (Fig. 2) are detailed in Table 1.

TABLE I

PREDICTED DURATION FOR INITIAL LOOSENING (IN WEEKS) OF VARIOUS ORTHOPAEDIC FIXATIVE SCREW DESIGNS IMPLANTED WITHIN THE FEMORAL HEAD

Screw Type	Time (in weeks)
Triangular	75
Triangular Wide	85
Trapezoidal	95
Trapezoidal Wide	106
Rectangular	95
Rectangular Wide	149

IV. DISCUSSION AND CONCLUSIONS

In the present study, dynamic simulations of bone adaptation were applied to predict cancellous bone resorption around orthopaedic fixative implants. The adaptation process, controlled by mechanosensors within the bone structure, was identified as an important cause of implant loosening and undesirable micromotion, in both animal experiments and patient studies [1], [2]. Because the stress shielding patterns causing the adaptation are dependant upon the material and geometrical characteristics of the fixative screw, the nature of the resulted bone resorption should also depend on the engineering design of the bone screw. Screw designs may thereby be optimized, in terms of selection of proper geometry and material properties, to produce as little bone loss as possible.

The bone-screw computational models are based upon several assumptions, which should be taken into account while interpreting the results. For example, the present approach of simulation employs an adaptation algorithm that relates local bone stiffness with respective bone density [3]. Some experimental variability was found in the stiffness-density relation. The differences are mainly related to the porous characteristic of the trabecular bone, which constitutes dependency in sites from which specimens are taken. Sensitivity analysis of the model to variations of up to 15% in the proportion coefficient of the stiffness-density relation [3] did not introduce significant changes in the results, in terms of the time-dependant stress distribution within the bone and the progress of implant loosening.

Finally, a method of evaluating and rating engineering designs and expected biomechanical performances of orthopaedic fixative screws was presented. The results indicated that a wide rectangular screw profile is of superior biomechanical compatibility with bone compared to the other profile types. The present work demonstrated that bone remodeling computer simulations can be used as a powerful tool for evaluation of several design parameters of the screws, such as geometry, material characteristics and even coatings.

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